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Research papers

A coupled model simulation assessment of shallow water-table rise in a Saudi Arabian coastal city

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Abstract

The problem of a rising shallow water-table level in the coastal city of Dammam in eastern Saudi Arabia was investigated through data collection, analysis, and numerical modelling. The research focused on applying a coupled model that considers flow in both the saturated and unsaturated zones. Geophysical and hydrogeological data were collected through field investigations, and various analyses of this data were performed. A computer simulation model of shallow groundwater flow was developed and applied to define the recharge sources. The generalised HYDRUS and MODFLOW modelling packages were coupled to simulate the vadose zone and saturated zone, respectively. The calibrated coupled groundwater model was used to determine the contributions of each possible recharge source, and thus to identify the major causes of the rise in the water table. The shallow water-table rise was found to be a serious threat to the present and future development of this large city.

Keywords: Shallow water table; Numerical model; Urban development; Coastal area; Water distribution network; Saudi Arabia

1. Introduction

Groundwater is in a state of constant flux, although it is often conceptualised as being static (Zektser and Loaiciga, 1993). Variations in the position of the water table are indications of the dynamic behaviour of the groundwater system. Connectivity between groundwater and surface hydrological processes is particularly strong in areas where shallow groundwater is present (Timms et al., 2001). A rising water level has been recognised as a precursor to flooding (Khaled et al., 2011). Recent instances of groundwater flooding in southern England and France have necessitated the inclusion of groundwater flooding in the 2007 European Union Floods Directive (Macdonald et al., 2012). The proximity of the water table to the land surface can seriously impact human activities. In particular, shallow water-table conditions are a major threat to building foundations and subsurface infrastructures in urban areas (Howard, 2002; Randall et al., 2013). A shallow water table can damage the foundations of structures, reducing their load-bearing capacity. Structures designed and constructed during periods of low water-table elevation are particularly vulnerable to rising groundwater levels (Morrison and Taylor, 1994). When the water table rises above the subsurface structures, a pressure gradient that enhances the infiltration of water through cracks and weaknesses in the structures develops. For example, in London (United Kingdom) and Dresden (Germany), a rising shallow water-table level has damaged both foundations and subsurface infrastructures (Greswell et al., 1994). Furthermore, in New York (USA), groundwater inflow into subsurface tunnels is a disturbing phenomenon (Kreibich and Thieken, 2008); and a rise in shallow water table was identified to have induced a landslide that destroyed multiple buildings in eastern Ukraine (Jakovljev et al., 2002).

Coastal areas are one of the settings in which a shallow water table is prevalent. This can be attributed to the characteristic low elevation of these areas. In coastal areas, land elevations approach sea level and, as groundwater flows towards the ocean, a hydraulic connection is created, resulting in shallow water-table conditions (Guo and Jiao, 2007). Studies by Small and Nicholls (2003) have indicated that approximately 40% of the world's population live in coastal cities, and approximately

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60% of the cities in the world with a population in excess of 5 million sit within these zones. Population pressure in coastal cities has made land reclamation an option in order to expand the areas of coastal land. The previously recognised hazards to which reclaimed land is vulnerable include storm surges, tsunamis and sea-level rise, but recently shallow water-table conditions have added a further dimension to the vulnerability of reclaimed coastal lands (Bondesan et al., 2000). The threats posed by a rising shallow water table to the development of coastal cities have only recently been acknowledged, and the causes have mostly been attributed to rainfall and sea-level rise in connection with climate change. However, examples in Uzbekistan and Ukraine have shown that a rising water table is also influenced by anthropogenic sources. High water-table conditions were created as a result of artificial recharge from water pipes and irrigation canals in urban areas of Uzbekistan (Ikramov and Yakubov, 2002). In eastern Ukraine, leaking water-supply systems and sewers were identified as the primary causes of a rise in water table that resulted in flooding over a large area (Jakovljev et al., 2002).

This study attempts to identify the causes of a rising shallow water table in the coastal city of Dammam in eastern Saudi Arabia. There is evidence that several building foundations and underground infrastructures in this city have been structurally weakened by the rising water table. Various sources, including precipitation, seawater intrusion and leakage from underground water networks and sewage pipes, were anecdotally suspected to be contributors to the rising shallow water-table problem. A careful investigation is therefore necessary to reach an adequate understanding of the problem, so that an appropriate mitigation plan can be put in place.

1.1. Study area

The area of study (Fig. 1) is Dammam city, one of the largest and most important administrative areas in Saudi Arabia. The city is the anchor of a substantially larger metropolitan area called Dammam Metropolitan Area, and it is the capital of the Eastern Province. It is located between latitudes 26.47° N and 26.30° N, and longitudes 49.93° E and 50.24° E, and bordered by the Arabian Gulf to the east and north-east. In 2010, the average minimum and maximum temperatures recorded in the area were 20.7°C and 35.5°C, respectively. The average precipitation rate was 6.39 mm/month; the highest recorded was 39.9 mm/month, and this occurred during the month of April. No rainfall was recorded from June to December. Relative humidity in the area ranged between 26 and 54%. Prevailing wind direction was northerly from January to September, and westerly from October to December. The average rate of wind speed was 4 m/s.

As a result of oil-production activities, its establishment as the administrative centre of the Eastern Province and development of the economic infrastructure and recreational facilities, the city has experienced a massive influx of people, and there was an upsurge in its population from 14,000 in the 1940s to 478,000 in 2005 (Alshuwaikhat and Aina, 2006). Today, the population of the city has increased to approximately 1,065,000. Distinctive land-use patterns have been established in the city; the most conspicuous among them are residential areas, government buildings, commercial areas, educational establishments, hospitals, parking areas and open space gardens, and a network of roads, including underpasses. The central part of the city is covered by Quaternary deposits. The deposits are locally characterised by a diversity of land types, including sand dunes, extensive sabkhas and the sea. The area is topographically low, with an average elevation of 3.5 m above mean sea level (AMSL). Phreatic water level in the area can rise to 2.5 m below mean sea level (BMSL). Much evidence exists that the shallow water-table condition has hindered the development of the city, as building foundations and engineered structures are under constant threat of groundwater incursion.

The area of study is situated on the Dammam dome, which is part of the sedimentary basins in eastern Saudi Arabia.

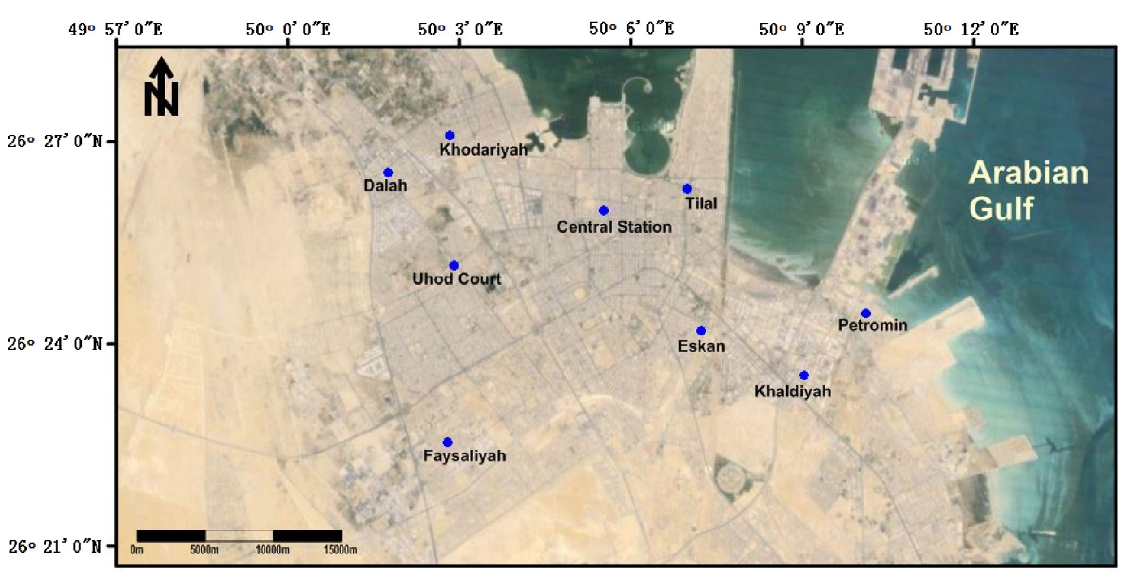

Fig. 1. Location map of the study area showing water level monitoring points.